An Assessment of Base Load Concentrating Solar Thermal Power Generation for New Zealand

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Abstract

With increasing pressure being placed on traditional energy sources, both in terms of supply and also regulatory, there is an increasing need to explore alternative generation technologies. In global terms, solar energy has the potential to make a significant contribution to worldwide energy demands in the future. This study examines recent developments in the emerging field of concentrating solar thermal power generation and explores the potential for base load electricity generation using this technology in New Zealand.

Introduction

In recent times there has been a growing concern over the use and availability of energy sources. These concerns have been driven by a number of factors including ensuring security of supply, increasing costs and environmental issues. There has also been a widespread realisation that the rate at which existing fuel sources, in particular fossil fuels, are being consumed is unsustainable. The result has been an increasing amount of research directed towards renewable energy technologies such as wind power, biomass and tidal power. In particular, the use of solar energy has been widely suggested as a means of reducing dependence on energy derived from fossil fuel sources.

In practical terms, the sun is the largest source of energy that is available to humanity. Each year it supplies in the order of 5.4 million EJ to earth of which 30% is reflected back into space. However, the remainder represents 10,000 times the world's consumption of fossil and nuclear fuel sources in the year 2002. Considering that in the same year, fossil and nuclear fuels provided over 80% of the world's energy consumption, there is significant potential to offset the use of these with solar energy (Boyle, 2004).

One shortcoming of the solar resource is its relatively low flux, typically 1kW/m^2 under good conditions. However this shortcoming can be overcome by focussing radiation from a large area onto a smaller area. The idea of focussing solar radiation to increase heat flux has a long history, from legends of Archimedes using it as a weapon against Roman war ships circa 200BC, through to its use in modern day power generation.

The modern age of concentrating solar power can trace its origins back to the late 19th century France, where Mouchot and Pifre developed a range of devices utilising parabolic dish steam boilers. However, due to increasing supplies of coal these early devices were unable to compete except in areas where coal was expensive. One such example was the development of a "large" scale plant in Egypt where Shuman demonstrated a parabolic trough plant producing 55hp. However, with the outbreak of WW1, and the rapid increase in oil supplies, such systems were mothballed (Boyle, 2004).

Towards the end of the 20th century, political instability and the first oil crisis, led to a renewed interest in the use of solar energy. As such in the early 1980's the first large scale solar plants (Solar 1, SEGS) were developed in southern California and the Mojave Desert (NREL, 2011). Again, at the beginning of the 21st century framed against population growth and increasing demand for resources resulting in significant increases in fuel costs, there is renewed interest in concentrating solar power as an energy source.

Concentrating Solar Power Technology

The concept behind concentrating solar power is relatively simple, reflective mirrors or lenses are used to focus energy from the sun to heat a receiver to high temperatures. The heat is then converted into mechanical energy using a turbine or other engine and subsequently into electricity.

The renewed interest in concentrating solar power has seen the emergence of four main technology types based on the manner in which the incoming solar radiation is focussed and captured. These broad classifications are:

- Parabolic troughs
- Linear Fresnel reflectors
- Solar towers
- Parabolic dishes

Parabolic Troughs

Parabolic troughs collectors are the most mature concentrating solar power technology and as such are the most widely used in current commercial solar power plants.

Parabolic trough collectors, as their name suggests, consist of a linear, parabolic mirror that focuses the radiation incident on them onto an absorber tube at the parabolas focus (Figure 1). The absorber tube is typically coated with a high temperature selective surface that absorbs a large amount of the ultraviolet, visible and near-infrared radiation but emits very little infra-red radiation. These tubes are then housed in an evacuated glass tube to prevent heat loss by convection. While operating, the parabolic mirrors and the absorber tube track the sun to maximise the energy received by the absorber tube and transferred to the working fluid.

Commercial parabolic trough power plants, such as the SEGS systems operating in the Mojave Desert, typically use synthetic heat transfer oils in their absorber tubes. Once heated the oil passes through heat exchangers, where water is preheated, evaporated and then superheated for use in a steam turbine (NREL, 2011).

Figure 1: Small parabolic trough reflector (no absorber tube shown)

Linear Fresnel Reflectors

Linear Fresnel concentrators approximate the parabolic shape of a trough system by utilising long rows of flat, or slightly curved, mirrors to reflect the sun's rays onto a downward-facing fixed linear absorber (Figure 2). The Linear Fresnel Reflector was initially developed in Italy by Francia (1968) who demonstrated an elevated linear solar boiler.

One of the principle advantages of Linear Fresnel systems is their relatively simple design, particularly in terms of the reflective elements, which can be flat rather than curved. The use of flat reflectors and fixed receivers leads to lower costs for Linear Fresnel reflectors (Mills and Morrison, 2000). Moreover such systems can facilitate direct steam generation, thus eliminating the need for intermediate heat transfer fluids and heat exchangers. However, their optical design means they are less efficient than troughs at converting solar energy to electricity.

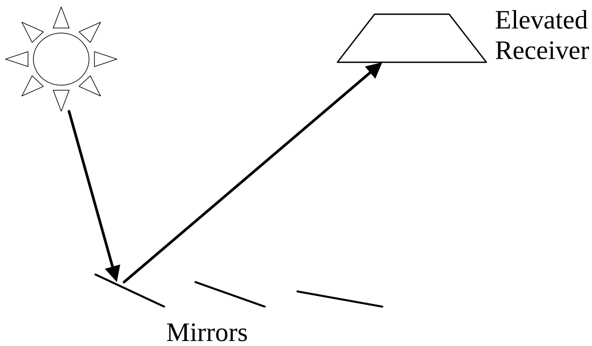

Figure 2: Schematic representation of a linear Fresnel reflector

A recent development to Linear Fresnel reflectors, known as compact linear Fresnel reflectors (CLFRs), uses two parallel receivers for each row of mirrors and thus needs less land than parabolic troughs to produce a given output. This style of system has raised the profile of linear fresnel technology and led to the development of systems in southern Spain (Novatec Solar, 2009), California (Areva), Newcastle, Australia (Ausra, 2004) and Kogan Creek, Queensland.

Solar Towers

Solar (power) towers or central receiver systems use large numbers of "small" mirrors (heliostats) to focus solar energy onto a receiver placed at the top of a fixed tower (Figure 3). The heliostats individually rotate on two axes, maintaining a focus on the receiver at the top of the tower. The flexibility of scale and number of heliostats can lead to very high concentration ratios and as such solar towers are well suited to large scale utility power generation. In this respect, the first sizeable examples of this style of system were the 10 MW Solar One and Solar Two plants established in the Mojave Desert during the 1980's, which have now been decommissioned (Gordon, 2001).

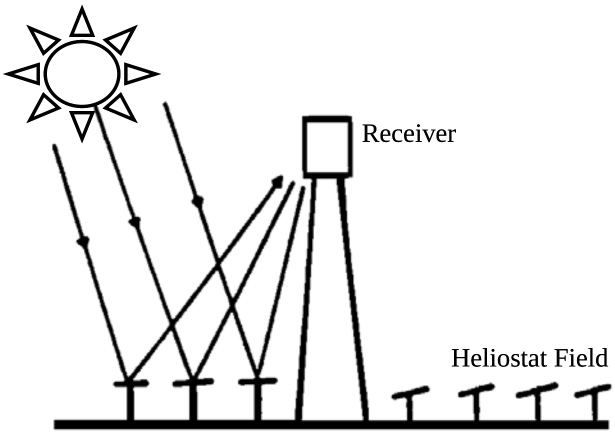

Figure 3: Solar tower system

Recently new systems have been developed in southern Spain by Abengoa Solar (PS10 - 11MW in 2007 and PS20 - 20MW in 2009) and in California by eSolar (Sierra SunTower - 5MW in 2009). The Australian commonwealth research organisation, CSIRO, has also constructed a small system as part of their research into high temperature solar energy at Newcastle, Australia (CSIRO, 2006).

The principle benefit of using the solar tower concept is that it is possible to achieve very high temperatures. These high temperatures lead to a marked increase in the efficiency at which heat is converted into electricity. Moreover, the concept provides a high degree of flexibility, such that designers can specify a wide variety and sizes of heliostats, receivers and transfer fluids.

Parabolic Dishes

Of all the concentrating solar technologies, parabolic dishes offer the highest solar-to-electric conversion performance. Parabolic dishes concentrate the incoming radiation to an absorber at the focal point above the centre of the dish while tracking the suns movement across the year (Figure 4). Historically, many dishes have had an independent generator such as a Stirling engine mounted at the focal point, eliminating the need for a heat transfer fluid and for cooling water. However, recently it has been proposed to utilise the heat generated by parabolic dishes to perform chemical dissociation of ammonia, to store as a fuel source (Lovegrove, 2004).

It has been suggested that mass production may allow parabolic dish technology to compete with other larger solar thermal systems. However dishes are relatively limited in size which means that large numbers of them would need to clustered together to create a large-scale plant as was done at White Cliffs in Australia during the early 1980's (Lovegrove and Dennis, 2006). More recently a plant has been proposed for development at Whyalla in South Australia (Taggart, 2008)

Figure 4: Australian National University SG4 Parabolic Dish

Thermal Storage for Solar Power Plants

In order to increase the competitiveness of concentrating solar power stations with existing technologies it is necessary for them to be able to provide dispatchable electricity. In warmer climates, peak electricity loads tend to be driven by cooling loads, which generally follow from high levels of solar radiation. However, solar radiation is not available at all times, and there is often high demand for electricity several hours after sunset. This means solar power plants need fossil fuel backup, or, as is now becoming common-place for solar power plants – thermal storage (Laing et al, 2006).

Although thermal power plants have a degree of thermal inertia, which represents short term storage suitable for minor variations in solar radiation, it is desirable to have storage that allows energy to be dispatched after the sun sets. The principle behind thermal storage is straightforward: throughout the day, excess heat is diverted to a storage material (typically molten salt) in much the same way that a solar water stores energy in a water cylinder. After the sun sets, the stored heat can be released back into the steam cycle allowing the solar power plant to continue generating power.

By varying the storage capacity, it is possible to smooth out variations in solar radiation and also to allow peak and shoulder loads to be met. Similarly, with large enough storage capacity it is possible to run solar power plants 24 hours a day. However, this depends on the economic viability of constructing large storage systems.

Concentrating Solar Power and New Zealand

As solar radiation enters the earth's atmosphere some passes directly through (direct or beam radiation) and some is scattered as it interacts with the atmosphere and suspended particles before it reaches the earth's surface (diffuse radiation). As such, under very clear skies the beam radiation represents the majority of the radiation reaching the earth's surface.

The beam radiation is of critical importance when considering high temperature solar energy systems as it can be concentrated, whereas the diffuse radiation cannot. Hence the energy utilised in concentrators is measured in terms of the direct normal irradiance, or the energy received by a surface tracked normal to the beam component of the solar radiation.

Typically direct normal irradiance is found to be best in arid and semi-arid areas along the earth's sun-belt, which falls in latitudes from 15° to 40° north or south. This has led to many studies highlighting the Sahara, southern California, Australia and the Middle East as potential sites for concentrating solar power stations (Trieb et al, 2009). In identifying these sites the studies typically use satellite data, of poor spatial resolution, to infer ground level radiation. As such New Zealand's small size does not allow its potential to be assessed by this method, despite the fact that it lies within the southern sun-belt.

Rather, taking ground station bright sunshine hour measurements as being indicative of direct normal irradiance, most areas in New Zealand receive in excess of 2000 hours per annum (NIWA, 2011). Additionally, towns such as Nelson, Blenheim, Whakatane and Napier receive close to 2500 bright sunshine hours annually, with the highest recorded number of hours being for Nelson in 1931, with 2731. Comparatively, Seville and Madrid in southern Spain, near where Abengoa Solar operate their solar towers, receive between 2700 and 2900 bright sunshine hours per annum. This suggests that areas of New Zealand represent potential sites for large scale concentrating solar power plants.

Case Study – Concentrating Solar Power near Nelson

Having identified the potential for solar concentrating power in New Zealand, it was decided to undertake a theoretical assessment of a two concentrating solar power systems with six hours of molten salt thermal storage operating near Nelson, using the SAM analysis package (NREL, 2010).

In terms of the establishment and operating costs for a concentrating solar power plant, it was assumed that the plant would have an operating life of 50 years, with an inflation rate of 2.5% and a real discount rate of 10% (The Treasury, 2011). During its operation corporate tax would be levied at a rate of 28%, sales taxes of 15%, and insurance levies at 0.5% would also be incurred.

Finance would provide a 40% debt fraction of the project for 30 years with interest of 4% and income generated by means of a power purchase agreement, increasing at a rate of 4%. It would also be expected that the plant would provide a minimum internal rate of return of 10% and, conservatively, would not be eligible for any incentive payments. Finally, engineering and project management costs were assumed to represent 15% and 3.5% of the indirect capital costs of the project.

For the first system, it was decided to analyse the performance of a 100MW plant using a solar trough field. Such a system would require approximately 900 acres for the field as well as the power block. The troughs were assumed to be using the Solargenix SGX-1 assembly and were 100m long with an aperture area of 5m. It was assumed that they would be coupled to a turbine with a net power output of 100MW.

In terms of the construction of the plant, it was assumed that: site improvements would cost $30/m^2$, the solar field $180/m^2$, the heat transfer system $90/m^2$, molten salt thermal stores \$15/kWht, power plant at \$800/kWhe, balance of systems \$200/ kWhe, contingency set at 10% and operation and maintenance of \$30/kW, similar to the values suggested by Price and Kearney (2003).

For the second system, it was decided to analyse the performance of a 100MW plant using a 200m high solar tower and heliostat field. Such a system would require over 700 heliostats each with an area of $144m^2$ and the total site would be in the order of 1200 acres. It was assumed that the solar tower would be coupled to a turbine with a net power output of 100MW.

For construction of the plant, it was assumed that: site improvements would cost $\$30/m^2$, the heliostat field $\$150/m^2$, molten salt thermal stores \$15/kWht, power plant at \$800/kWhe, balance of systems \$200/ kWhe, solar tower \$15.3M, receiver \$10.1M, contingency set at 10% and operation and maintenance of \$30/kW, similar to the values suggested by Hinkley et al (2011).

From the analysis, it was found that both trough and solar tower type systems would deliver approximately 200,000 MWh per annum as shown in Figure 5.

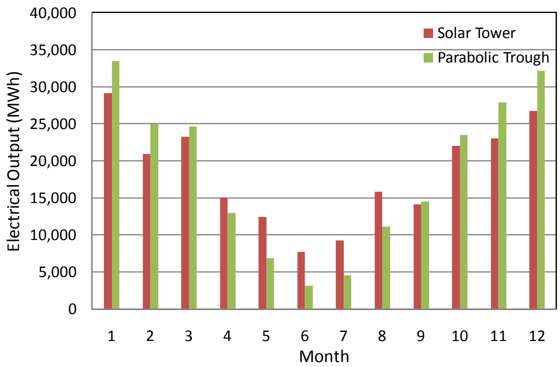

Figure 5: Output from solar power plant near Nelson

Perhaps more importantly, it was found that in both instances that the systems would deliver electricity for a nominal levelised cost of electricity of approximately \$200/MWh, similar to that paid by domestic consumers (MED, 2011). Although this is higher than wind, and obviously gas and coal, it should be noted that the analysis has been relatively conservative, and has not taken into account any tax incentives. Moreover, it should be noted that the US Department of Energy has set targets for its concentrating solar power programme to reach competitiveness with fossil fuels at \$100MWh by 2015 and to have reached \$50MWh by 2020 (IEA, 2010). Based on this projected trajectory, it is highly likely that these levels could be reached by concentrating solar plants in New Zealand too, within the next decade.

Conclusion

With increasing pressure being placed on traditional energy sources and so there is an increasing need to explore alternative generation technologies. Solar energy has been shown to offer potential significant contributions to electrical energy demands in the future. From the work undertaken here, it has been shown that New Zealand's solar resource is world class for concentrating solar power and that the development of large scale solar power plants could be feasible at a number of locations. It was also shown that the levelised cost of electricity generated by concentrating solar power was already at a level similar to that paid by domestic consumers. Given the levelised cost of electricity from concentrating solar is expected to reduce further, there may be an opportunity for this technology in New Zealand into the future.

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